SCIENCE FOR GLASS PRODUCTION

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AN ENERGY-RELATED METHOD FOR DETERMINING IMPACT STRENGTH IN SHEET GLASS

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A new method based on the energy-related approach is proposed for predicting sheet glass impact strength. The method is tested for annealed and hardened glass.

The specifics of sheet glass applications in vehicles, construction, and transparent protective enclosures dictate testing which involves an impact inflicted by a hard object. The impact-inflicting test bodies are usually hardened steel spheres of varying weight (GOST 5727–88) thrown from a prescribed height, whereas laminated bullet-proof structures are tested by shooting under the conditions prescribed by GOST 51136–98.

Considering the variety of glass structures (single-layer, hardened, laminated, triplex), the shape and weight of the impact body, and the particular properties of tested articles with respect to elasticity, plasticity, and other parameters, the problem consists in analytical determination of the fracture conditions for single-layer glass, or the depth of penetration of a falling body into a multilayer glass structure.

The present article is an attempt to predict impact strength for one-layer glass.

Such types of predictions were offered before [1 – 3] and were based on introducing the dynamics coefficient known in the theory of the strength of materials, although the particular material specifics were not fully taken into account.

A new fracture model is proposed here, taking into account the specifics of the GOST 5727–88 test, which makes it possible to verify its adequacy.

The tested glass sample is a plate supported by a square contour (Fig. 1*a*). The impact body (a spherical steel globe) of weight *m* is dropped onto the glass surface from height *H*. Therefore, we will henceforward consider a plate of thickness *d* having the hinge contour support.

The following phases in the interaction of the sphere and the plate can be identified in the course of glass fracture.

In the first phase, the sphere freely falls from height *H* and contacts the plate surface (Fig. 1 a). The sphere velocity by that moment will be

$$v_0 = \sqrt{2gH},$$

where g is the free fall acceleration, and its kinetic energy

$$E_0 = \frac{mv_0^2}{2}.$$

Elastic deformation of both the plate and the globe occurs at the second phase (this is conventionally indicated in Fig. 1*b*).

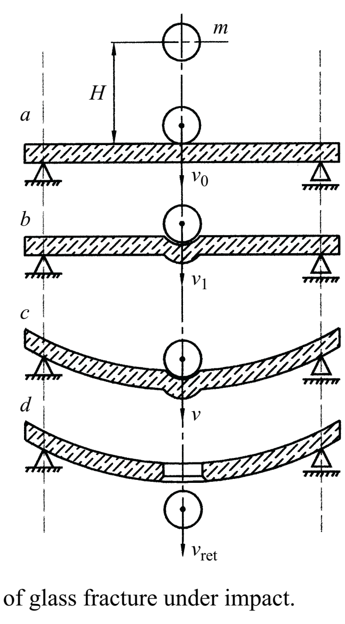

Fig. 1. Model of glass fracture under impact.

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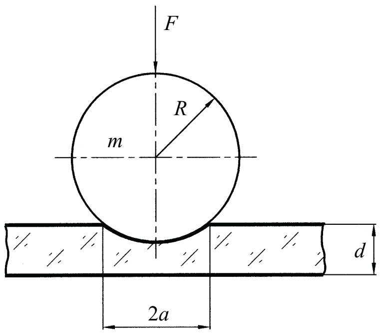

Fig. 2. Scheme of interaction between the sphere and the surface.

This kind of deformation is accompanied by energy consumption, as the result of which the velocity of the sphere decreases to v_1. The potential energy of elastic deformation

$$E_{el} = E_{el.s} + E_{el.gl},$$

decreases the kinetic energy of the sphere to the level

$$E_1 = \frac{mv_1^2}{2}.$$

The next phase is the movement of the sphere and the plate as a whole, whereas the plate is elastically bent under the effect of a concentrated force (Fig. 1*c*).

The sphere energy is spent on bending the plate and is equal to E_b.

If the conditions of the contact between the bodies exceed the carrying capacity of the plate, the glass article is broken through (Fig. 1*d*). In this case, the sphere may have a certain residual velocity v_{res} and the kinetic energy

$$E_{res} = \frac{mv_{res}^2}{2}.$$

Let us denote the energy spent on destroying the plate as E_f.

Based on the above model, the following energy balance is obtained:

$$E_0 = E_{el.s} + E_{el.gl} + E_b + E_f + E_{res}. \tag{1}$$

Let us consider each component separately.

The scheme of local elastic deformation is shown in Fig. 2. All the relationships for the sphere are known:

the volume

$$V = \frac{4}{3}\pi R^3;$$

the weight

$$m = V\rho,$$

where ρ is the density of the sphere material.

In the quasistatic variant according to Hertz [4], the contact of the sphere with the surface can be represented as an indentation with the formation of a circular area having the characteristic size

$$a = 0.88\sqrt[3]{FR\left(\frac{1}{E_s} + \frac{1}{E_{gl}}\right)},$$

where F is the indentation force; E_s and E_{gl} are the elasticity moduli of the materials of the sphere and the glass, respectively.

The greatest stresses arise in the center of the contact area

$$\sigma_{max} = 0.388\sqrt[3]{\frac{4F}{R^2}\frac{E_s^2E_{gl}^2}{(E_s + E_{gl})^2}}.$$

A complex stressed state arises in the contact area with the principal stresses as follows:

$$\sigma_3 = -|\sigma_{max}|; \tag{2}$$

$$\sigma_1 = \sigma_2 \approx -0.8\,|\sigma_{max}|. \tag{3}$$

The specific potential deformation energy (energy per volume unit) is found from the formula

$$e = \frac{1}{2E}(\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)),$$

where μ is the Poisson coefficient, and taking into account relationships (2) and (3) we obtain

$$e = 1.14\frac{\sigma_{max}^2}{E}(1 - 1.825\mu).$$

It appears possible to use this expression in order to determine at least three components of balance (1).

The potential energy of the elastic deformation of the sphere

$$E_{el.s} = eV,$$

or

$$E_{el.s} = 1.14\frac{\sigma_{max}^2}{E_s}\frac{4}{3}\pi R^3(1 - 1.825\mu),$$

or, taking σ_{max} equal to the glass elasticity limit σ_{el}, provided $\mu = 0.3$, we get

$$E_{el.s} = 2.16\frac{\sigma_{el}^2}{E_s}R^3.$$

Henceforward the selection of the volume to which the destructive stress action will be extended is of special signifi-

cance. The studies indicate that the breakthrough of glass is accompanied by the formation of a hole with a conical part (Fig. 3). Considering the hole diameter and the depth of its conical part, the total fracture volume will be equal to:

$$V_{\mathrm{gl}} = 1.75\pi R^2 d.$$

The potential energy of the elastic deformation of the plate at $\mu = 0.22$ will be:

$$E_{\mathrm{el.gl}} = 3.759 \frac{\sigma_{\mathrm{el}}^2}{E_{\mathrm{gl}}} R^2 d,$$

and the potential glass fracture energy can be calculated from the latter relationship, taking into account the glass ultimate strength.

The potential energy of the total elastic bending of the plate was found earlier [4]:

$$E_{\mathrm{b}} = \frac{mv_0^2}{2}\left(1 + \frac{1}{2}\frac{m_{\mathrm{pl}}}{m}\right)^{-1},$$

where m_{pl} is the plate weight.

The above described approach to the calculation of the impact strength of glass was verified based on the known experimental results for annealed and hardened glass.

The analysis demonstrated that for the mean statistical energy of a falling sphere, the error of the proposed method does not exceed 5%.

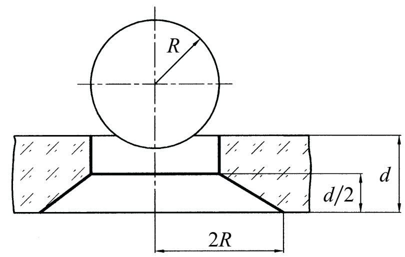

Fig. 3. Scheme of breakthrough in the glass sheet.

It is suggested that the specified method be extended to solving a wide range of strength problems for laminated construction and bullet-proof glass.

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